REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-99-

0252

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL REPORT 1 Mar 98 to 31 Aug 98

4. TITLE AND SUBTITLE
UAV AEROSERVOELASTIC CONTROL USING REDUNDANT MICROACTUATORS

5. FUNDING NUMBERS
F49620-98-1-0299
2307/AS/BS
61102F

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
110 DUNCAN AVENUE SUITE B115
BOLLING AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This program is aimed at an improved understanding of nonlinear aeroservoelastic characteristics for uninhabited air vehicles and the evaluation of innovative approaches to UAV control. The work focuses on redundant micro-actuators, and includes the development of methods for aeroservoelastic anlaysis and design applicable to a wide/range of control strategies. The concepts are of use in the control of vehicles such as high altitude, endurance (HAE) UAV's involving significant aeroelastic coupling with the vehicle dynamics, or uninhabited combat air vehicles (UCAV's) which require rebust control in the presence of observability constraints and aerodynamic nonlinearities.
The investigation includes eveluation of a new trailing edge effector concept and control law design algorithms required for its synthesis. The multidisciplinary approach involves researchers from several fields, and includes studies of the fluid mechanics of such devices, an innovative approach to manufacturing, and novel control design methods that are well suited to this concept. Present work involves computational and experimental validation tests leading to more comprehensive development and testing in future work.

19991101 043

14. SUBJECT TERMS

15. NUMBER OF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
U	U	U	

N/A

UAV AEROSERVOELASTIC CONTROL USING REDUNDANT MICROACTUATORS

Final Report for:
AFOSR Contract No. F49620-98-1-0299

14 OCT 1999

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Abstract
This program is aimed at an improved understanding of nonlinear aeroservoelastic characteristics for uninhabited air vehicles and the evaluation of innovative approaches to UAV control. The work focuses on redundant micro-actuators, and includes the development of methods for aeroservoelastic analysis and design applicable to a wide range of control strategies. The concepts are of use in the control of vehicles such as high altitude, endurance (HAE) UAV's involving significant aeroelastic coupling with the vehicle dynamics, or uninhabited combat air vehicles (UCAV's) which require robust control in the presence of observability constraints and aerodynamic nonlinearities.

The investigation includes evaluation of a new trailing edge effector concept and control law design algorithms required for its synthesis. The multidisciplinary approach involves researchers from several fields, and includes studies of the fluid mechanics of such devices, an innovative approach to manufacturing, and novel control design methods that are well suited to this concept. Present work involves computational and experimental validation tests leading to more comprehensive development and testing in future work.

Two major areas are addressed here:

1. *UAV aeroservoelastic control using micro-trailing-edge actuation.* The concept involves replacing conventional aerodynamic control surfaces with a large number of small actuators at the trailing edge of lifting surfaces. Two basic approaches are being investigated, each involving fabrication of "meso-scale" components using new manufacturing techniques. The resulting controls are robust and redundant. They are small, simple devices that do not require local servo feedback or accurate position measurement and are well-suited to low observable aircraft. Because the surfaces are distributed they provide an excellent opportunity for structural mode control.

2. *Aeroelastic analysis and nonlinear ASE design optimization with redundant micro-actuators* The approach to flexible vehicle analysis and control design must be appropriate for use with these micro-actuator concepts. This is particularly important since some of these actuators are very nonlinear or are designed to operate in discrete states rather than in a conventional continuous manner. We are investigating innovative approaches to nonlinear aeroelastic analysis

and optimization that include collocation-based methods for simultaneous analysis and design[1], and control schemes that provide more general architectures than those generally assumed for aircraft flight control.

Micro-trailing-edge-effectors

Micro Trailing-edge Effectors (MITEs) are small surfaces located near the trailing edge of a wing that are deflected to large angles, effectively controlling the circulation near the trailing edge and modifying the zero-lift-angle. Best known in their application as lift enhancing tabs or Gurney flaps, they have been shown to enhance the lift characteristics of single and multi-elements airfoils [2,3]. Their advantages, as control devices, are their high frequency response, high authority up to stall conditions, and high effectiveness in manipulating the section lift and aerodynamic moment in addition to their mechanical simplicity. Section lift coefficient increments between 0.2 to 0.8 may be achieved at a given angle of attack depending on the airfoil type and flap size. One of the more important features of these devices is their effectiveness near stall and the respective increase of $C_{L\max}$ especially for swept wings (up to 35% maximum wing lift increase). The forces required to actuate these microflaps are minute compared to the wing lift increase, so they have a very high control effectiveness and may potentially be used as primary controls at both low and high lift conditions. Initial estimates show that MiTE devices of 1% height produce control forces similar to 15° deflection of 30% regular or slotted flaps. However, aerodynamic hinge moments and moments of inertia are expected to be 1 to 3 orders of magnitude smaller.

Due to their small size and inertia, these micro flaps can be actuated much more rapidly than conventional wing controls. This leads to higher bandwidth and response that will enable control of high frequency phenomenon such as buffet and aeroelastic modes. Unlike conventional control surfaces, failure of some of these surfaces is not critical since many redundant surfaces are employed. Furthermore, the aerodynamic characteristics of these actuators are such that failure of the surfaces, even without mass balancing, do not lead to aeroelastic instabilities. Such devices have been used primarily at a single fixed deployment angle of 90° on the wing lower surface; the present work will include investigations of the performance of these surfaces in a dynamic environment.

A computational study is being used to predict the effectiveness of MITEs as control devices, and identify unsteady phenomena that may affect the controller design. Though this concept offers the potential for revolutionary miniaturized and efficient control, its characteristics as a high frequency effector are not well understood. Since micro flaps can be deployed quickly and traverse a relatively large range of local attack angles, conventional methods to analyze, predict and design aerodynamic controls may not be adequate. Since the time constant is expected to be of same order as the time required for local flow changes to affect global forces, complex coupling and transient response are expected. The mechanism of operation is highly viscous, so these unsteady characteristics are also expected to be non-linear and difficult to predict without detailed numerical or experimental investigation. This portion of the research extends the current computational work at Stanford [2] using 2D Navier-Stokes CFD analysis. This includes analyses of a full range of deflection angles, hinge moment characteristics, and subsequent evaluation of flow time-constants required for control system synthesis.

Phase I Program Results

The first phase of work on this program was intended to identify the most promising approaches and uncertainties, and to demonstrate the basic feasibility of the concept for aeroelastic control. This required a very focussed multidisciplinary program of design, analysis, fabrication, and test that resulted in our selection of the miniature trailing-edge effector (MiTE) scheme and which proved surprisingly successful.

MiTE aerodynamics and design

Initial aerodynamic analysis work was undertaken to compare two competing concepts for distributed control using local manipulation of the trailing edge flow field. Techniques that involved normal blowing near the trailing edge and boundary layer suction on a section designed to be especially sensitive to boundary layer growth near the trailing edge, were studied using 2D Navier-Stokes models and the MSES airfoil analysis code. Results suggested that although significant control forces could be generated in this way, the power and mass flow required made the concept unattractive for UAV applications. By contrast, previous experimental data and Navier-Stokes simulation showed that, at least in the steady flow case, very small trailing edge flaps, deflected to +/- 90° could provide the required control inputs with hinge moments two to three orders of magnitude smaller than that of conventional controls. CFD analysis was used to size the microflaps and to estimate the pressures required for pneumatic actuation. MSES and PANDA airfoil codes were then used to design a section that would operate predictably at the Reynolds numbers available in the Stanford University wind tunnel, while providing sufficient depth for instrumentation and plumbing. The section was designed with small aft loading to assure effective microflap operation at large deflections over a large angle of attack range.

A key part of the first phase of this study was the development of a 2D simulation capability. This required a Navier-Stokes solution since the microflaps rely fundamentally on local flow separation to achieve their high effectiveness. The incompressible Reynolds Averaged Navier-Stokes solver, INS2D, developed at NASA Ames Research Center, was used for this purpose. A computational grid that provided sufficient resolution near the microflap region was designed as shown in figure 1.

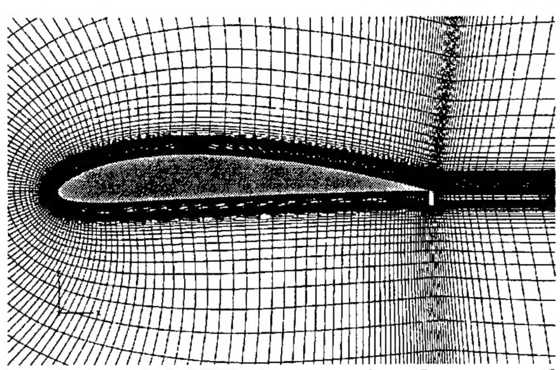

Figure 1. CFD Grid around airfoil with MiTE showing detail near trailing edge region.

Balwin-Barth and Spalart-Almuras turbulence models were found appropriate in this case, while the simpler Baldwin-Lomax model was not sufficient. Converged steady results were obtained for a variety of flap

sizes, section shapes, and flow conditions. Detailed results (see figure 2) compare well with earlier experiments on "Gurney flaps" and permitted the first look at required hinge moments. Quasi-steady results were generated for the expected wind tunnel test conditions and compared with experimental data (see figure 5). The reasonable agreement permitted us to defer development of the time-accurate unsteady model to Phase II, although this is required for proper prediction of control lags and maximum bandwidth.

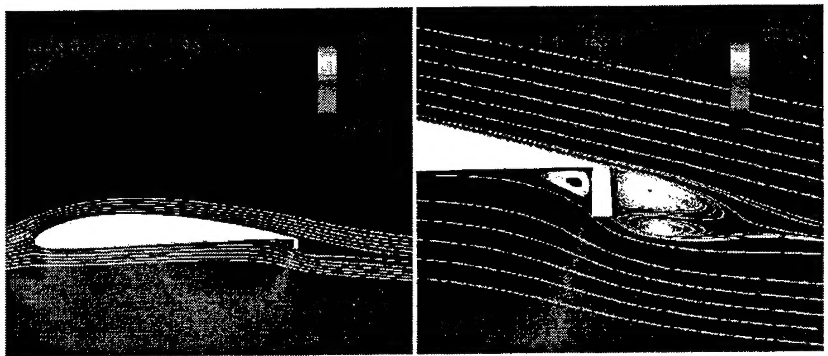

Figure 2. Solutions from Navier-Stokes simulation of section with 90 deg deflected flap

Shape Deposition Manufacturing for the Fabrication of Microflaps

Shape Deposition Manufacturing (SDM) [4] is a layered manufacturing technology, developed for the fabrication of functional, multi-material, macroscopic, and mesoscopic parts and assemblies. Using a layered approach, SDM systematically combines the advantages of material additive processes with the precision of traditional material removal processes. To provide fixturing each part is built encased in a sacrificial support structure which is removed after the build process is completed. The basic fabrication strategy of SDM slices a CAD model into layers, with geometry dependent thickness, which preserve the 3D geometry of the outer surface. Each layer is further decomposed into layer segments, called 'compacts', according to the following rules: 1. Each compact is composed of a single material. 2. Each contains the 3D geometric information of the outer surfaces and multi-material interfaces. 3. Undercut surfaces are not directly shaped, but formed through molding or shape transfer by previously fabricated compacts. Decomposition of the microflap according to these rules greatly reduced shape complexity and allowed largely automated process planning of the micro flap assembly. Figure 3 shows the layer decomposition and indicates the order in which the compacts were fabricated. Each compact is manufactured by depositing material (in the case of the flaps, polyurethane served as part material and wax as support material) as a near-net shape in the first step of each process cycle. In a second step the material is accurately machined to net-shape before the deposition and material removal cycle is repeated for successive compacts. Using a flexible and programmable manufacturing concept, SDM allows the implementation of any number of different deposition and forming processes. Other intermediate processing operations, such as internal stress control, inspection, or embedding of prefabricated components such as sensors and actuators e.g. micro valves, can be added to individual SDM cycles as required.

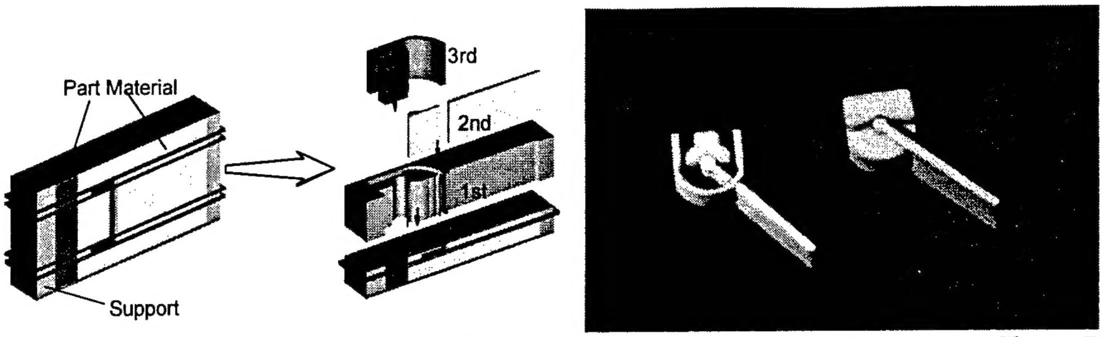

Figure 3. Decomposition and build-up of complex, multiply connected geometries using Shape Deposition Manufacturing. On right, completed polyurethane MiTE showing pneumatic chamber.

The microflaps are fabricated in parallel batches. In Phase I we built 17 devices in each batch. The devices emerge from the process as complete assemblies, ready to be fastened to the airfoil trailing edge. In Phase I of this work, several designs for a pneumatically-actuated microflap were fabricated. Although significant advances could be made in actuator efficiency and response by reducing tolerances, and more complete systems including integral control valves were envisioned, a simple version of the device proved workable for the experiment and, because of limited time in Phase I, these were manufactured.

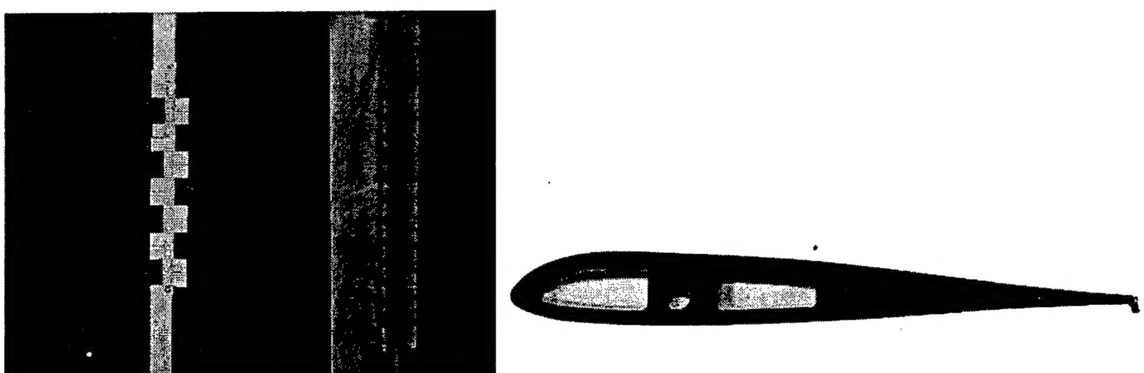

Figure 4. Test section profile and aft view of microflaps deflected in pairs and in a single block.

Experimental Investigation

Experimental Apparatus: The aerodynamic response experiments were conducted in our Flow Control Wind Tunnel, a closed-loop subsonic wind tunnel with excellent flow uniformity and freestream turbulence below 0.2%. The tunnel test section is 61 cm wide by 91 cm high by 4 meters long. The freestream velocity can be varied from 0 to 20 m/s under computer control. The balance, an AMTI MC3A-6-1000 six-component load cell, was chosen for optimal sensitivity for the present measurements. The data acquisition from the balance and flow sensors, the wind tunnel speed control, and the operation of the distributed control system are all performed by two Dell Pentium II-based PC's equipped with National Instruments interface boards and LabView software.

The model was NC-machined, based on coordinates from the aero design study, using solid blocks of Dupont Renshape 450, a rigid polymer with excellent dimensional stability and machining properties. Internal passages were made to allow installation of internal pneumatic tubing for microflap actuation. The 61 cm chord wing spanned the tunnel vertically and was mounted on the balance via a fitting that allowed the angle of attack to be varied. Both the support structure and wing are rigid so that the maximum deflection of the free end of the wing is less than 1 mm at maximum wind tunnel speed.

Sixteen microflaps with 1 cm chord and span were attached to the trailing edge midway over the span. The pneumatically actuated flaps are controlled by supplying high pressure air to one of the two supply ports on each flap. For the initial tests, pressure tubing was connected to each microflap and routed through the internal passages of the wing to a pneumatic control system beneath the tunnel. The pressure lines were attached to eight solenoid valves so that each valve controlled two adjacent flaps. Each valve was controlled by a single line of the computer's digital I/O port through a power relay. Thus, a total of 256 different microflap configurations could be realized, and the configuration varied in less than 50 milliseconds. Since the flaps occupied only the central 16 cm of the wing span, fixed flaps were mounted over the rest of the span to simulate microflaps uniformly actuated in one direction.

Results: Baseline tests were performed with the airfoil at zero angle of attack, the fixed flaps removed, and the microflaps at zero deflection. Additional static tests were performed with all of the flaps (fixed and operable) in the downward and upward positions. At 20 m/s freestream velocity, the Reynolds number based on the actual chord length of 57.7 cm is 735,000. A boundary layer trip was installed 7.6 cm downstream of the airfoil leading edge to ensure uniform transition. The resulting lift and pitching moment were found to be strongly dependent on flap position and relatively independent of Reynolds number. The measured coefficients agree closely with the CFD predictions made during the design phase, confirming the control potential of the microflap approach. Additional static tests were performed by changing the position of the 16 microflaps while leaving the fixed flaps in the down position. These tests give an estimate of the expected control effectiveness using only the part-span microflap array. Changing the flap positions from down to up decreases C_L (averaged over the entire wing) from 0.43 to 0.33 and C_M from 0.11 to 0.08. The corresponding section C_L change is +/- 0.30 which is equivalent to approximately 6 degrees change in section incidence. The dynamic response of the airfoil to flap actuation was examined for two different actuation waveforms and at two different actuation rates. The applied actuation signal to each flap was a square wave since there is no provision for proportional control of the flap position. Figure 5 shows the measured load coefficients for a case in which the entire block of 16 flaps was oscillated together at a frequency of 1 Hz, corresponding to a reduced frequency, k, of 0.088 based on the wing semi-chord. The plot shows that the response of C_L and C_M is very repeatable and follows the square wave input signal, albeit with several strong harmonics. Phase-shifted harmonics and an overshoot in C_L are apparent in the Phase I data and indicate that the dynamics of the flow play a significant role in the wing response. A second set of dynamic experiments was performed with the block of flaps controlled as eight separate pairs, each deflected out of phase with the adjacent pair. The phase lag between each pair was identical , producing a traveling wave along the block. This case showed reduced harmonics and the expected smoother behavior that would be typical of the controlled response in which a gradual range of control force is generated by deflecting a fraction of the devices as required. The same two flap waveforms were investigated for an actuation frequency of 10Hz, corresponding to a reduced frequency of 0.88. This frequency range was at the high end of the actuator capability and one or two flaps would frequently not fully extend, leading to minor disturbances in the measured load waveforms.